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Fertilizer Use Efficiency in Climate-smart Agriculture: Balancing Yield, Emissions, and Soil Health

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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Abstract

Global agriculture faces a compound challenge: producing sufficient food for a growing population while dramatically reducing its environmental footprint. Fertilizers—particularly synthetic nitrogen compounds—underpin modern crop yields, yet their overuse drives nitrous oxide (N_2O) emissions, nitrogen leaching, soil

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acidification, and threats to planetary biogeochemical cycles. Climate-smart agriculture (CSA) offers an integrative framework that seeks simultaneously to raise productivity, build resilience, and reduce greenhouse gas (GHG) emissions. Central to this framework is fertilizer use efficiency (FUE), defined broadly as the ratio of crop output relative to nutrient inputs. This critical review synthesises evidence across the global literature on the agronomic, environmental, and soil-health dimensions of FUE in CSA systems. Drawing on peer-reviewed research published predominantly since 2001 to present; it evaluates the mechanisms by which conventional fertilizer management contributes to GHG emissions and soil degradation; examines enhanced-efficiency fertilizers, precision agriculture, integrated soil fertility management, biochar, cover crops, and biological nitrogen fixation as mitigation pathways; and assesses the tensions between maximising yield and minimising environmental harm. The review identifies significant advances in FUE technologies and management but also highlights persistent knowledge gaps, particularly around context-specific adoption barriers in smallholder systems, long-term soil health trajectories, and coherent policy architectures. A synthesis of the evidence suggests that no single intervention is adequate; rather, portfolios of complementary, site-adapted practices—underpinned by robust policy incentives—are necessary to reconcile food security, climate mitigation, and soil health within planetary boundaries.

Keywords: Fertilizer use efficiency; climate-smart agriculture; nitrogen management; soil health; integrated nutrient management; precision agriculture.

1. Introduction

Climate change is intensifying constraints on agricultural productivity by amplifying nutrient losses, yield instability, and environmental degradation. Climate-smart agriculture (CSA) seeks to address these challenges by integrating productivity, resilience, and sustainability; however, conventional fertilizer practices remain inefficient and environmentally burdensome. Recent advances in nano-fertilizer technologies offer new opportunities to improve nutrient management within CSA frameworks (Rasel et al., 2026). A major challenge for agricultural sustainability is to conserve ecosystem service delivery while optimizing agricultural yields. This Special Issue addresses the task to find a balance between increasing yields using conventional and novel fertilizers, and the maintenance of soil and environmental health as a basis for the sustainable intensification of the agricultural sector (Krasilnikov et al., 2022).

1.1 The Global Fertilizer Imperative

The capacity of synthetic nitrogen fertilizers to sustain high crop yields has been one of the defining achievements of the twentieth century. Nitrogen fertilizer application rates were based on empirical observations and traditional practices, where farmers applied fertilizers according to their experiences and generalized recommendations. This often led to inefficiencies and potential environmental consequences due to the lack of precision in matching fertilizer inputs with specific crop and soil requirements. Early precision N management practices were significantly shaped by soil testing, which provided critical insights into soil conditions and nutrient availability, enabling more informed and targeted fertilizer applications (Cai et al., 2025). The Haber–Bosch process, which fixes atmospheric nitrogen into reactive compounds, fundamentally transformed global food systems over the past century (Erisman et al., 2008), and is estimated to directly support the nutrition of approximately half of the world's human population (Zhang et al., 2015). Global nitrogen fertilizer use has risen steadily since the mid-twentieth century, and this trajectory shows little sign of reversal: by 2018, the synthetic nitrogen fertilizer supply chain was responsible for estimated emissions of approximately 1.13 $GtCO_2e$, representing 10.6% of total agricultural GHG emissions and 2.1% of total global GHG emissions (Menegat et al., 2022). Phosphorus (P), the other principal macronutrient, carries its own long-term scarcity risk, with phosphate rock reserves finite and unevenly distributed globally (Cordell et al., 2009).

The environmental consequences of this fertilizer-dependent system are severe and well-documented. Globally, only approximately 50% of the nitrogen applied to crops is taken up by plants, with the remainder lost through volatilisation, leaching, and denitrification (Lassaletta et al., 2016). In cereal crops specifically, which account for the largest share of synthetic nitrogen use worldwide, recovery efficiency is often substantially lower—below 40% in many systems—reinforcing the gap between theoretical and practical NUE (Sandhu et al., 2021). These losses constitute a cascade of problems: nitrous oxide—a greenhouse gas roughly 265–298 times more potent than CO_2 over a 100-year horizon—is released during nitrification and denitrification in soils; nitrate contaminates groundwater and surface water, driving eutrophication; and ammonia volatilisation contributes to atmospheric reactive nitrogen deposition (Galloway et al., 2008). Agricultural soils are responsible for approximately 50% of the total global anthropogenic N_2O flux (Shcherbak et al., 2014), and N_2O emissions from global croplands have quadrupled over the period 1961–2020 (Cui et al., 2024). Globally, human nitrogen and phosphorus inputs to the biosphere have transgressed the safe operating boundaries originally proposed by Rockström et al. (2009), a situation updated and confirmed by Richardson et al. (2023), who identified that six of nine planetary boundaries are now exceeded, including those for biogeochemical flows of both nitrogen and phosphorus.

At the same time, agricultural nutrient balances are deeply inequitable. Parts of sub-Saharan Africa remain severely under-fertilised, with average nitrogen application rates far below those needed to maintain soil fertility, whereas large areas of East Asia and Europe are burdened by substantial nutrient surpluses (Vitousek et al., 2009; Lassaletta et al., 2016). This dual problem—excess and deficiency—makes a global "one-size-fits-all" approach to fertilizer management not only impractical but potentially counterproductive.

Climate-smart agriculture has emerged as a conceptual and policy framework seeking to reconcile food production, climate adaptation, and mitigation. As articulated by Zheng et al. (2024), CSA constitutes innovations aligned with three objectives: sustainably increasing agricultural productivity and incomes; adapting and building the resilience of people and food systems to climate change; and reducing or avoiding GHG emissions where possible. Fertilizer use efficiency sits at the centre of all three pillars: it governs crop yield and farmer income, influences soil resilience to climate variability, and determines the scale of emissions from nutrient inputs. Yet, as Cassman and Grassini (2020) note, progress towards sustainable intensification—of which FUE improvement is a core component—remains behind schedule, reflecting a complex interplay of technological, institutional, and socioeconomic barriers.

1.2 Definitions and Framing

Fertilizer use efficiency encompasses several distinct but interrelated indicators. Nitrogen use efficiency (NUE) is most commonly defined as the ratio of crop nitrogen uptake to total nitrogen applied; phosphorus use efficiency (PUE) follows analogous logic; while the broader concept of nutrient use efficiency may encompass agronomic efficiency, apparent recovery efficiency, physiological efficiency, and partial factor productivity, each capturing a different dimension of the nutrient–yield relationship (Mueller et al., 2012; Tilman et al., 2002). This review uses FUE as an umbrella term encompassing these metrics, with emphasis on nitrogen given its dominant role in both crop production and GHG emissions.

1.3 Scope and Objectives

This critical review examines the evidence on fertilizer use efficiency in the context of CSA across the full agronomic–environmental spectrum. It addresses the following objectives: (1) to characterise the GHG emissions arising from fertilizer production and field use, and their sensitivity to management choices; (2) to evaluate the mechanisms by which soil health is affected by fertilization regimes; (3) to critically appraise the evidence on enhanced-efficiency fertilizers, precision agriculture, integrated soil fertility management, organic amendments, cover crops, and biological nitrogen fixation as pathways to improved FUE and reduced emissions; (4) to assess the trade-offs and co-benefits among these approaches in the context of climate variability; and (5) to identify research gaps and policy implications for operationalising FUE within CSA frameworks. No citations are included in this subsection, which is devoted to outlining the scope and purpose of the review.

2. Methods for Literature Selection

2.1 Databases and Search Strategy

The literature underpinning this review was retrieved from the following databases: Web of Science, Scopus, Google Scholar, and PubMed as general scientific databases; and some databases particularly relevant to the subject: AGRIS – Food and Agriculture Organisation of the United Nations (FAO) publications repository, the CGIAR online library, AGRICOLA – USDA National Agricultural Library, the CAB Abstracts – CABI, AGORA – Research4Life / FAO, DOAJ – Directory of Open Access Journals, Dimensions and OpenAlex.

Search strings were constructed from combinations of the following terms: "fertilizer use efficiency," "nitrogen use efficiency," "climate-smart agriculture," "nitrous oxide emissions," "soil health," "organic amendments," "precision agriculture," "nitrification inhibitors," "controlled-release fertilizers," "integrated soil fertility management," "biochar," "cover crops," "biological nitrogen fixation," and "greenhouse gas mitigation." Boolean operators (AND, OR) were used to combine terms systematically, and wildcard characters were applied where relevant. The date range was restricted primarily to 2001–2026, with classic foundational references incorporated where they remain authoritative and widely cited.

2.2 Review Approach and Study Selection

A narrative rather than systematic review approach was adopted. This choice is supported by Green et al. (2006), who argue that narrative reviews are particularly well suited to synthesising heterogeneous literature across multiple disciplinary domains, integrating insights from diverse methodological traditions, and identifying broader conceptual and policy implications that a strictly quantitative systematic approach would not easily capture. The subject of FUE in CSA spans agronomy, soil science, atmospheric chemistry, ecology, and political economy; the diversity of experimental designs, ecological contexts, cropping systems, and measurement approaches across the global literature makes it poorly amenable to the standardised inclusion and exclusion criteria of a systematic meta-analysis.

Screening proceeded in two stages. Titles and abstracts were first evaluated against relevance criteria: papers had to address at least one of the five review objectives, be published in a peer-reviewed journal or an authoritative institutional report, and be available in English. Studies that were duplicates, or that were superseded by more comprehensive meta-analyses, were excluded. Book chapters, conference abstracts, trade magazines, patents, and grey literature were excluded throughout. A second screening stage examined full texts to assess quality, methodological rigour, and the extent to which key claims were supported by primary data. Where multiple meta-analyses addressed the same phenomenon, the most recent and comprehensive were prioritised, supplemented by earlier foundational studies. No language restriction was imposed in the search phase, but only papers with full-text availability in English were retained for citation.

3. Greenhouse Gas Emissions from Fertilizer Production and Field Use

3.1 The Carbon Footprint of Nitrogen Fertilizer Manufacture

The manufacturing of synthetic nitrogen fertilizers via the Haber–Bosch process is energy-intensive, relying predominantly on natural gas as both a feedstock and energy source. Erisman et al. (2008) estimated that by the early twenty-first century, the Haber–Bosch process was responsible for the synthesis of more than half the nitrogen in the human body worldwide, illustrating the extraordinary scale of industrial nitrogen production and its centrality to global food systems. Menegat et al.(2022) estimated that the synthetic nitrogen fertilizer supply chain generated approximately 1.13 $GtCO_2e$ in 2018, representing 2.1% of total global GHG emissions. Within that total, fertilizer production accounted for 38.8% of supply-chain-associated GHG emissions, field emissions accounted for 58.6%, and transportation accounted for the remaining 2.6%. Improvements in production technology—including electrolysis-based "green ammonia" routes powered by renewable energy—could substantially reduce the production-side footprint, though at present such technologies remain commercially marginal (Zhang et al., 2015). The implication for CSA is that even perfectly efficient field application cannot eliminate the embedded carbon cost of manufactured nitrogen unless upstream production pathways are simultaneously decarbonised.

3.2 Nitrous Oxide from Agricultural Soils

N_2O is simultaneously a potent greenhouse gas and the dominant stratospheric ozone-depleting substance emitted in the present era. Thompson et al. (2019) demonstrated an acceleration in global N_2O emissions over two decades of atmospheric inversion analysis, and Tian et al. (2020) subsequently provided a comprehensive global synthesis confirming that human-induced N_2O emissions increased by approximately 30% between 1980 and 2016, with direct and indirect agricultural sources comprising by far the largest anthropogenic contribution. The fertilizer–N_2O relationship is nonlinear: as demonstrated by Shcherbak et al. (2014) in a global meta-analysis of studies using multiple fertilizer rates, N_2O emissions increase exponentially rather than linearly with nitrogen application above agronomic optima. This finding has profound implications for CSA: reducing fertilizer application from surplus to optimal rates yields disproportionately large reductions in N_2O emissions. Cui et al. (2024) estimated a global mitigation potential of 0.7 Tg N_2O-N yr^{-1} from croplands without compromising crop production, with 86% of this potential arising from optimised nitrogen fertilization alone.

3.3 Nutrient Losses beyond N_2O

Beyond direct N_2O emissions, the environmental consequences of nitrogen inefficiency include nitrate leaching to groundwater, ammonia volatilisation, and downstream eutrophication of freshwater and coastal ecosystems. Galloway et al. (2008) characterised this as a "nitrogen cascade," whereby reactive nitrogen released at one environmental compartment sets off a chain of biogeochemical and ecological transformations that are difficult to predict and costly to remediate. Phosphorus losses, meanwhile, are particularly problematic in the context of long-term resource security: Cordell et al. (2009) estimated that global phosphate rock reserves may face depletion or critical quality decline within 50–100 years, with a production peak forecast around 2030, though exact timelines remain contested. These twin challenges—P scarcity and N pollution—underline the importance of closing nutrient cycles, increasing the efficiency of nutrient use, and integrating organic nutrient sources into fertilization strategies.

Table 1 summarises the principal GHG emission pathways associated with the nitrogen fertilizer lifecycle, together with estimated emission magnitudes. The table makes clear that field-level N_2O emissions dominate the supply-chain footprint and that cropland emissions have grown substantially over recent decades, affirming the critical role of agronomic management in determining agricultural GHG outcomes. These magnitudes should be read alongside the finding that reducing excess nitrogen application generates disproportionately large emission benefits because of the exponential, rather than linear, nature of the N_2O dose–response relationship (Shcherbak et al., 2014).

Table 1. Primary greenhouse gas emission pathways in the nitrogen fertilizer lifecycle

Emission Pathway	Primary Process	Approximate Global Magnitude	Key Reference
N_2O from cropland soils (direct)	Nitrification and denitrification	~1.2 Tg N_2O-N yr^{-1} (2020)	Cui et al. (2024)
N_2O indirect (leaching, volatilisation)	Nitrate runoff; NH_3 deposition	Substantial but highly variable by region	Tian et al. (2020)
CO_2e from N fertilizer production	Haber–Bosch energy use	~38.8% of 1.13 $GtCO_2e$ supply-chain total	Menegat et al. (2022)
Total supply-chain GHG (CO_2e)	Production + field + transport	1.13 $GtCO_2e$ yr^{-1} (2018); 2.1% of global GHG	Menegat et al. (2022)
NH_3 volatilisation (indirect N_2O precursor)	Urea hydrolysis; atmospheric deposition	Highly variable by management	Galloway et al. (2008)

GHG = greenhouse gas; $GtCO_2e$ = gigatonnes of CO_2 equivalent; Tg = teragrams

4. Soil Health Dimensions of Fertilizer Management

4.1 Soil Organic Carbon Dynamics

Soil organic carbon (SOC) is a foundational indicator of soil health, underpinning nutrient cycling, water retention, aggregate stability, microbial biodiversity, and long-term crop productivity. The relationship between synthetic fertilization and SOC is nuanced. Han et al. (2016) conducted a global meta-analysis of SOC changes under four contrasting fertilizer management regimes—unbalanced chemical fertilizers (UCF), balanced chemical fertilizers (CF), chemical fertilizers plus straw (CFS), and chemical fertilizers plus manure (CFM)—and found that topsoil organic carbon increased by 10.0%, 15.4%, 19.5%, and 36.2%, respectively, relative to unfertilised controls. This hierarchy demonstrates that the addition of organic carbon inputs alongside mineral fertilizers substantially improves SOC outcomes, and that organic matter inputs are at least as important as fertilizer balance in determining SOC trajectories. At the broader scale, Beillouin et al. (2023) synthesised findings from 230 first-order meta-analyses comprising over 25,000 primary studies in a second-order meta-analysis of SOC in the Anthropocene, confirming that land conversion to cropland leads to high SOC loss, recoverable only partially through land management practices. Practices that incorporate exogenous carbon—

biochar, organic amendments, agroforestry—were among the most effective at rebuilding depleted SOC stocks. Paustian et al. (2016) outlined the substantial mitigation potential in climate-smart soils, suggesting that improved land management could deliver annual carbon sequestration rates in agricultural soils of approximately 0.9–1.85 Pg C yr^{-1} under improved management scenarios, equivalent to a substantial fraction of current agricultural GHG emissions. However, these potential gains are constrained by the permanence of storage, measurement uncertainties, and the risk of loss under future climate change, particularly in warmer and drier regions (Paustian et al., 2016; Beillouin et al., 2023).

4.2 Soil Acidification and Nutrient Imbalances

Long-term use of acidifying nitrogen fertilizers—particularly ammonium sulphate and urea—contributes to progressive soil acidification, reducing phosphorus availability, mobilising phytotoxic aluminium and manganese ions, and suppressing beneficial microbial communities. Vitousek et al. (2009) highlighted the stark divergence in nutrient balances globally: while some regions suffer from severe nutrient deficits limiting soil fertility, others—particularly parts of intensive agriculture in Europe, China, and the United States—are burdened by chronic nutrient surpluses that acidify soils and pollute water. Mueller et al. (2012) demonstrated that closing yield gaps in underperforming areas without increasing environmental pressures requires spatially explicit, balanced nutrient management, rather than the blanket application of the same fertilizer rates that characterise high-input systems.

4.3 Soil Biological Communities

Repeated high-rate nitrogen applications alter the composition of soil microbial communities, often suppressing fungal diversity while stimulating bacterial dominance, and can reduce the populations of nitrogen-fixing and phosphate-solubilising microorganisms that underpin natural nutrient cycling. The relationship between fertilization intensity and soil biodiversity is not simply linear, and ecological context matters greatly. Organic amendments—including compost, manure, and green manures—generally maintain or enhance microbial diversity compared to exclusive reliance on synthetic inputs (Foley et al., 2011). These biological effects have cascading consequences for soil function: reductions in mycorrhizal colonisation under high-phosphorus conditions reduce the ability of plants to access P from diverse soil pools, creating a dependency cycle on external inputs.

Table 2 summarises the key mechanisms by which different fertilizer management approaches affect principal soil health indicators. As the table illustrates, approaches that integrate organic inputs with mineral fertilizers consistently outperform sole mineral fertilization across all measured dimensions of soil health, from SOC content and pH buffering to microbial diversity and N_2O emission intensity. These outcomes are discussed in greater detail in the context of specific management strategies in Section 5.

Table 2. Relative effects of different fertilizer management regimes on soil health indicators

Soil Health Indicator	Mineral-Only High Rate	Balanced Mineral + Organic	Integrated Nutrient Management	Key Reference
Soil organic carbon	Often neutral or declining	Moderate increase	Large increase	Han et al. (2016)
Soil pH buffering	Tends to decline (acidification)	Moderate pH buffering	Improved with organic inputs	Vitousek et al. (2009)
Microbial diversity	Often reduced	Maintained	Enhanced	Foley et al. (2011)
Nitrogen leaching risk	High	Moderate	Lower with timing optimisation	Abdalla et al. (2019)
N_2O emission intensity	High at excess rates	Moderate	Reduced under good practices	Shcherbak et al. (2014)
Phosphorus use efficiency	Variable	Improved	Highest under ISFM approaches	Vanlauwe et al. (2010)

ISFM = integrated soil fertility management

5. Pathways to Improved Fertilizer Use Efficiency

5.1 Enhanced-Efficiency Fertilizers

Enhanced-efficiency fertilizers (EEFs) include controlled-release formulations, urease inhibitors, and nitrification inhibitors—all designed to synchronise nutrient release or retention with crop uptake demand, thereby reducing losses.

Nitrification inhibitors slow the bacterial oxidation of ammonium to nitrate, sustaining a plant-available nitrogen pool while reducing leaching and N_2O production. The two most widely studied compounds are dicyandiamide (DCD) and 3,4-dimethylpyrazole phosphate (DMPP). Tufail et al. (2023) conducted a meta-analysis of 146 peer-reviewed studies and found that DCD and DMPP were equally effective in reducing N_2O emissions, while DCD was more effective at increasing plant productivity; crop-specific and soil-specific factors strongly modulated these outcomes. Earlier work by Abalos et al. (2014) established a grand mean crop yield increase of 7.5% and NUE improvement of 12.9% from the combined use of urease and nitrification inhibitors across a range of environmental and management contexts. A particular caution from Tufail et al. (2023) is that DMPP can, under some conditions, increase ammonia volatilisation—a potential negative trade-off that requires attention in management planning, particularly on soils with higher pH and at elevated application rates.

Controlled-release fertilizers (CRFs) employ polymer or sulphur coatings that regulate nutrient release in response to temperature, moisture, or time. By matching release rate to crop demand, CRFs can achieve substantial reductions in both leaching and emissions. Zhang et al. (2022) analysed Chinese agronomic data through a meta-analysis and found that controlled-release urea can effectively substitute for the split application of conventional urea, achieving comparable grain yields while improving NUE in most circumstances. Shcherbak et al. (2014) identified that any reduction in applied nitrogen above the agronomic optimum generates exponentially greater N_2O emission reductions, a dynamic that CRFs can exploit by ensuring lower, sustained nutrient concentrations in the soil solution.

5.2 Precision Agriculture and Digital Tools

Precision agriculture uses geospatial and remote-sensing technologies to tailor nutrient inputs to within-field spatial and temporal variability. Variable-rate fertilizer application systems, guided by soil sensors, satellite multispectral imagery, unmanned aerial vehicles (UAVs), and decision support algorithms, can reduce total fertilizer inputs without sacrificing yield by applying more only where and when crops need it. Getahun et al. (2024) reviewed the application of precision agriculture technologies globally and confirmed their role in enhancing productivity while reducing carbon footprints, with GPS-guided machinery, remote sensing, and Internet of Things (IoT) sensor networks all contributing to more targeted management. The economic case for precision agriculture is strengthening as sensor costs decline and data analytical capacity expands. However, adoption remains highly uneven: the technology is far more accessible to large commercial farms in temperate regions than to smallholder farmers in sub-Saharan Africa or South and Southeast Asia, where crop nutrient deficits are most acute. Cassman and Grassini (2020) argued that closing the gap between current and attainable yields requires machine learning and geospatial frameworks that allow site-specific management solutions to be developed and disseminated efficiently at scale.

5.3 Integrated Soil Fertility Management

Integrated soil fertility management (ISFM) was formally defined by Vanlauwe et al. (2010) as a set of soil fertility management practices that necessarily include the use of fertilizer, organic inputs, and improved germplasm combined with the knowledge of how to adapt these practices to local conditions, aimed at maximising agronomic use efficiency. Originally developed in the context of sub-Saharan Africa—where soil nutrient mining and chronic underuse of fertilizers combine to depress yields severely—ISFM has proven applicable across diverse agro-ecological and socioeconomic contexts.

ISFM does not replace mineral fertilizers but rather harnesses the synergistic interactions between mineral and organic inputs: organic matter improves cation exchange capacity and moisture retention, enhancing the efficiency with which mineral fertilizers are used. Field evidence from across sub-Saharan Africa demonstrates that ISFM can double or treble maize yields in areas where sole application of mineral fertilizers at low rates had limited agronomic impact (Vanlauwe et al., 2010). The approach also builds SOC over time, contributing to the soil health improvements documented by Han et al. (2016).

5.4 Biochar as a Soil Amendment

Biochar—a carbon-rich solid produced by pyrolysis of biomass at low oxygen concentrations—has attracted considerable attention as a soil amendment capable of simultaneously improving crop yields, enhancing SOC stocks, and reducing N_2O emissions. Beillouin et al. (2023) confirmed biochar's role as one of the most effective interventions for partially restoring SOC in degraded cropland soils. Paustian et al. (2016) characterised biochar as a climate-smart soil technology with high sequestration potential per unit area. The mechanisms through which biochar improves FUE include increasing soil pH in acidic soils, thereby reducing P fixation and aluminium toxicity, improving water-holding capacity, and creating a habitat that supports beneficial microbial communities. At the same time, biochar effects on N_2O emissions show context-dependency: while many studies report reductions, outcomes vary with biochar feedstock, application rate, soil type, and climate, and require further long-term field study before confident generalisations can be made (Paustian et al., 2016; Beillouin et al., 2023).

5.5 Cover Crops and Nitrogen Cycling

Cover crops—non-harvested crops grown between cash crop cycles—serve multiple FUE-enhancing functions: they reduce nitrate leaching by capturing residual soil nitrogen, can suppress weeds, maintain ground cover, and, when leguminous, contribute biologically fixed nitrogen to the system. Abdalla et al. (2019) conducted a critical global review and found that cover crops significantly reduce nitrogen leaching, with effects strongest in humid and cool regions. Their effects on N_2O emissions were variable: leguminous cover crops that deposit large amounts of easily mineralised nitrogen-rich residue can transiently increase N_2O emissions at residue incorporation, potentially offsetting some leaching-reduction benefits if management is suboptimal. This highlights the importance of matching cover crop species, termination timing, and residue management to local conditions. For CSA, the overall net greenhouse gas balance of cover cropping is generally favourable due to SOC accumulation and reduced synthetic fertilizer requirements, but careful management is required to avoid short-term emission trade-offs (Abdalla et al., 2019).

5.6 Biological Nitrogen Fixation and Legume Integration

Legumes fix atmospheric nitrogen symbiotically through Rhizobium associations, contributing biologically fixed nitrogen at agronomically significant rates under productive conditions—rates that can substantially reduce dependence on synthetic nitrogen inputs in subsequent crops within the rotation (Galloway et al., 2008). This biologically fixed nitrogen has a lower carbon cost than manufactured nitrogen and generates considerably less N_2O per unit of nitrogen added to the soil (Foley et al., 2011). Integration of grain legumes and pasture legumes into rotations is a well-established practice for reducing synthetic nitrogen demand; in sub-Saharan Africa, dual-purpose grain legume–maize rotations constitute a core element of ISFM (Vanlauwe et al., 2010). However, legume-derived nitrogen is slow-release and variable in quantity, limiting the extent to which it can fully substitute for synthetic nitrogen in high-productivity systems. Moreover, cultivation of nitrogen-fixing legumes is not without its own N_2O footprint, as a portion of biologically fixed nitrogen follows the same denitrification pathways as fertilizer nitrogen (Tian et al., 2020).

5.7 The 4R Nutrient Stewardship Framework

The 4R framework—applying the right nutrient source, at the right rate, at the right time, and in the right place—is perhaps the most widely endorsed operational guide to FUE improvement in agronomic practice. While simple in concept, its implementation requires integration of soil testing, crop demand estimation, weather forecasting, and adaptive management, all of which demand agronomic knowledge, extension support, and in some contexts, digital tools. Zhang et al. (2015) demonstrated explicitly that regional and national policies—including subsidy reform, fertilizer price signals, and agronomic advisory services—are as important as any single agronomic technology in determining whether farmers adopt efficient practices at scale.

6. Trade-offs and Tensions between Yield, Emissions, and Soil Health

6.1 The Yield–Emissions Trade-off

Perhaps the most fundamental tension in fertilizer management is the partial positive correlation between yield and N_2O emissions at the field level: as nitrogen rates increase above the agronomic optimum, crop yield plateaus while emissions increase exponentially (Shcherbak et al., 2014). Mueller et al. (2012) demonstrated that eliminating nutrient overuse in high-input regions could allow an approximately 30% increase in major cereal production by simultaneously closing yield gaps in underperforming regions—without any increase in global nutrient inputs. This redistributive logic is elegant in theory but difficult in practice: it requires international coordination, market restructuring, and addressing deep inequities in fertilizer access. Foley et al. (2011) elaborated the broader case, arguing that tremendous progress could be made towards sustainable agricultural production by halting agricultural expansion, closing yield gaps on underperforming lands, and increasing cropping efficiency simultaneously.

Cui et al. (2024) estimated that 86% of the global N_2O mitigation potential from croplands lies in optimising nitrogen fertilization rates, emphasising that the largest emission reductions are achievable from moderate adjustments in already-intensive systems rather than from eliminating fertilizer use. This finding has important policy implications: it suggests that GHG mitigation and food production need not be in fundamental conflict if fertilizer rates in surplus regions are brought to agronomic optima.

6.2 Soil Health and Productivity Trade-offs

High-rate synthetic fertilization can sustain or increase short-term crop yields while simultaneously degrading soil health over longer timescales through acidification, SOC depletion, and microbial community disruption. Tilman et al. (2002) made this observation in a landmark review of agricultural sustainability, and it remains relevant more than two decades later. The irony is that soil health degradation ultimately undermines the very productivity that intensive fertilization was intended to support, creating a dependency cycle in which ever-greater inputs are required to compensate for declining soil function.

ISFM and organic amendments offer pathways to break this cycle by investing in soil capital, but they typically require larger initial investments in knowledge, time, and sometimes financial resources than simple mineral fertilizer application. Zheng et al. (2024) reviewed evidence that CSA practices collectively improve farm productivity and incomes in many contexts, but noted that trade-offs between efficiency, inclusivity, and resilience remain and must be managed contextually rather than assumed to resolve themselves automatically.

6.3 Climate Change as a Complicating Factor

Climate change itself alters the dynamics of fertilizer management. Rising temperatures accelerate nitrogen mineralisation and denitrification, potentially increasing N_2O emissions per unit of applied nitrogen; altered rainfall patterns modulate leaching and volatilisation losses; and extreme weather events can cause catastrophic nutrient losses from fields. Cassman and Grassini (2020) warned that these dynamic interactions complicate the task of achieving yield stability with reduced inputs and underline the need for adaptive management frameworks that incorporate real-time climate data. Tian et al. (2020) confirmed that climate-driven changes in soil moisture and temperature significantly modulate the magnitude and timing of N_2O pulses from agricultural soils, suggesting that static fertilizer recommendations based on historical climate norms will become increasingly inadequate as the climate continues to change.

Conversely, improved FUE can contribute to climate mitigation directly by reducing N_2O emissions and indirectly by reducing the carbon footprint of nitrogen manufacture (Menegat et al., 2022). Paustian et al. (2016) outlined the substantial mitigation potential in climate-smart soils, noting that the transition to practices that build SOC—cover crops, reduced tillage, biochar, organic amendments—generates co-benefits in terms of enhanced soil water retention and drought resilience, which are themselves adaptations to climate change. This positive feedback reinforces the attractiveness of FUE improvement as a component of integrated CSA strategies.

7. The Global Context: Equity, Policy, and Scaling

7.1 Inequalities in Fertilizer Access and Use

A recurring theme in the global literature is the stark inequality between over-supplied and under-supplied agricultural systems. While parts of Europe, East Asia, and North America struggle with nutrient surpluses and their attendant pollution, large areas of sub-Saharan Africa—home to hundreds of millions of smallholder farmers—suffer from chronic nutrient depletion that drives soil degradation and food insecurity (Vitousek et al., 2009; Vanlauwe et al., 2010). Lassaletta et al. (2016) tracked nitrogen flows in global food systems over fifty years and found that international food trade has disconnected crop and livestock production, creating structural N surpluses in exporting regions and deficits in importing ones. Sutton et al. (2013) estimated that approximately USD 800 billion is lost annually through nitrogen pollution globally, while hundreds of millions of people in low-income countries simultaneously lack access to the nutrients needed to grow sufficient food. Addressing this asymmetry requires not merely technical solutions but structural policy reforms: reducing fertilizer subsidies that drive overuse in wealthy nations, improving fertilizer access and affordability in low-income ones, and aligning international trade rules with sustainability objectives. Foley et al. (2011) proposed a suite of integrated solutions for sustainable agriculture that explicitly includes redirecting nutrient flows from wasteful to productive uses as a central element, alongside ceasing agricultural expansion into natural ecosystems.

7.2 Fertilizer Policy Instruments

The policy landscape for fertilizer management is complex. Price incentives—including taxes on excess nitrogen application, subsidies for precision agriculture technology, and payments for ecosystem services tied to FUE improvements—can all modify farmer behaviour, but their effectiveness depends heavily on institutional context, price elasticity, and the availability of affordable alternatives. Zhang et al. (2015) argued that policy reforms must be tailored to regional nitrogen management trajectories: strategies appropriate for intensive systems in China differ fundamentally from those needed in sub-Saharan Africa. Mueller et al. (2012) demonstrated empirically that closing yield gaps through balanced nutrient management could dramatically increase food production in underperforming regions without increasing global nutrient inputs, provided that overuse in surplus regions is simultaneously curtailed.

The CSA framework, as characterised by Zheng et al. (2024), recognises that building enabling policy environments—including research investment, extension services, input market reform, and institutional support for farmer organisations—is as important as the technical content of agronomic recommendations. Richardson et al. (2023) argued more urgently that the current transgression of biogeochemical planetary boundaries for nitrogen and phosphorus demands structural reform of global food systems, not merely incremental efficiency improvements.

7.3 Smallholder Constraints and Technology Transfer

Smallholder farmers, who produce a substantial share of food in developing countries, face distinctive barriers to FUE improvement. Financial constraints limit investment in soil testing, precision equipment, and enhanced-efficiency fertilizers; knowledge constraints hamper optimal application timing and rates; and market imperfections mean that the environmental benefits of improved management are not internalised as economic returns for the farmer. Vanlauwe et al. (2010) emphasised that ISFM succeeds in smallholder contexts precisely because it is knowledge-intensive and adaptable, rather than dependent on expensive inputs—but its scaling requires robust extension systems that remain underfunded in much of sub-Saharan Africa. Digital agriculture offers potential to reach smallholders more effectively through mobile advisory services, remote-sensing-based alerts, and AI-driven decision support (Getahun et al., 2024). However, Cassman and Grassini (2020) cautioned that technology deployment must be preceded by investment in the agronomic knowledge base, without which digital tools risk providing precise answers to the wrong questions.

Table 3 summarises the principal strategies for FUE improvement examined in this review, their documented GHG mitigation potential, yield effects, soil health effects, and key implementation constraints. The table reveals a clear and consistent pattern: strategies that integrate multiple mechanisms—biological, chemical, and digital—tend to deliver the broadest co-benefits, while the most environmentally effective approaches often require the greatest knowledge and institutional support to implement successfully. This reinforces the need to embed technical solutions within enabling social and policy frameworks rather than pursuing agronomic innovation in isolation.

Table 3. Summary of key FUE improvement strategies in CSA systems, with estimated environmental and agronomic effects and implementation constraints

Strategy	N_2O Reduction Potential	Yield Effect	Soil Health Effect	Primary Constraint	Key Reference
Nitrification inhibitors (DCD/DMPP)	30–50% reduction	+5–10%	Variable	Cost; soil-type specificity	Tufail et al. (2023); Abalos et al. (2014)
Controlled-release fertilizers	Substantial; context-dependent	Comparable to split application	Neutral to positive	High unit cost	Zhang et al. (2022); Shcherbak et al. (2014)
Precision agriculture (variable rate)	Significant; highly context-dependent	Maintained to improved	Neutral to positive	Technology access; data infrastructure	Getahun et al. (2024)
Integrated soil fertility management	Moderate	+50–200% in nutrient-deficient areas	Strongly positive	Knowledge-intensive; extension access	Vanlauwe et al. (2010)
Biochar application	Variable; often 10–30% reduction	Positive in acidic and degraded soils	Strongly positive (SOC)	Production cost; feedstock availability	Paustian et al. (2016); Beillouin et al. (2023)
Cover crops	Variable; potential short-term spike at termination	Neutral to slightly reduced short-term	Strongly positive (SOC, biodiversity)	Management timing and species selection	Abdalla et al. (2019)
Biological N fixation (legume integration)	Low direct emissions per unit N	Positive in rotation context	Positive	Rotation management; residue N_2O risk	Foley et al. (2011)
Rate optimisation / 4R framework	Up to 86% of global feasible cropland mitigation	Maintained at optimum rates	Positive long-term	Agronomic advisory capacity	Cui et al. (2024); Zhang et al. (2015)

SOC = soil organic carbon

8. Synthesis: Navigating the Trade-off Landscape

8.1 Toward a Portfolio Approach

The body of evidence reviewed here strongly suggests that there is no singular, universal solution to the challenge of improving FUE in CSA systems. Rather, the evidence points to the value of context-adapted portfolios of practices that exploit complementarities and manage trade-offs. The most effective documented strategies are those that combine complementary mechanisms: for example, the joint application of nitrification inhibitors and precision application timing can achieve synergistic reductions in N_2O emissions while maintaining yield; the combination of ISFM with improved germplasm in sub-Saharan Africa routinely outperforms either practice in isolation; and the integration of biochar, organic amendments, and balanced mineral fertilizers has been shown to generate larger SOC gains than any single amendment applied alone (Han et al., 2016; Beillouin et al., 2023).

Mueller et al. (2012) demonstrated the magnitude of the opportunity: global closing of yield gaps through better nutrient and water management could increase cereal production by 45–70% without expanding agricultural land, while simultaneously eliminating overuse in surplus regions could reduce environmental damage without reducing global food output. Foley et al. (2011) made a similar argument, proposing that globally redistributed and more efficiently used nitrogen and phosphorus inputs could feed a growing world population within a smaller environmental envelope. What is missing is not so much the technological knowledge—much of which is now available—but the institutional architecture, policy instruments, and financial mechanisms to implement it at scale.

8.2 Monitoring, Reporting, and Verification

A persistent challenge for CSA implementation is the difficulty of reliably measuring and verifying emissions reductions and soil carbon sequestration at farm scale. Paustian et al. (2016) identified measurement uncertainty and the lack of standardised monitoring systems as a major barrier to including soil carbon in climate policies. Remote sensing, proximal soil sensors, and soil modelling frameworks offer promising approaches, but their application in low-resource settings remains limited. Digital agriculture platforms can potentially facilitate more cost-effective monitoring (Getahun et al., 2024), but data gaps in developing countries remain acute, and standardised protocols have yet to be universally adopted.

8.3 Research Gaps

Several knowledge gaps merit explicit acknowledgement. First, the long-term trajectories of soil health under different FUE management regimes remain insufficiently characterised, particularly in tropical and subtropical environments where climate sensitivity is greatest. Second, the interactions among multiple simultaneous interventions—nitrification inhibitors, biochar, precision agriculture, and ISFM—have rarely been studied in combination, leaving important knowledge gaps about synergies and antagonisms. Third, the socioeconomic barriers to adoption in smallholder systems are well-described but insufficiently addressed by research that focuses primarily on biophysical outcomes. Fourth, while global estimates of N_2O mitigation potential are increasingly robust (Cui et al., 2024; Tian et al., 2020), spatially explicit, crop-specific, and management-specific assessments are needed for effective policy targeting. Fifth, the acceleration of N_2O emissions documented by Thompson et al. (2019) and Tian et al. (2020) underscores an urgent need for monitoring systems capable of detecting management-induced improvements at regional scales in near-real time.

9. Conclusions

This review has documented that fertilizer use efficiency is a pivotal determinant of whether agriculture can simultaneously meet the ambitious demands of food security, climate mitigation, and soil health within the operational space of CSA. The global nitrogen fertilizer system, as it currently functions, generates substantial and largely avoidable environmental harm: it contributes over one gigatonne of CO_2-equivalent emissions annually through the fertilizer supply chain, drives nonlinear increases in N_2O emissions at supraoptimal application rates, and transgresses biogeochemical planetary boundaries for both nitrogen and phosphorus. At the same time, under-fertilization in much of the developing world perpetuates soil degradation and food insecurity.

The evidence reviewed supports a clear conclusion: meaningful improvement in FUE is not only environmentally necessary but agronomically and economically beneficial when implemented with appropriate management. Nitrification inhibitors, controlled-release fertilizers, precision agriculture, integrated soil fertility management, biochar, cover crops, and legume integration each offer demonstrated benefits in specific contexts. However, realising the full potential of these approaches requires moving beyond isolated, single-intervention thinking to portfolio-based, adaptive management frameworks that are calibrated to local ecological, economic, and social conditions.

The CSA framework provides a useful integrative lens, but its operationalisation demands strong enabling policy environments: reformed subsidy systems, investment in extension services and digital infrastructure, and institutional mechanisms to internalise the environmental benefits of improved FUE as economic incentives for farmers. Without these structural changes, even the most technically sound agronomic innovations will struggle to achieve the scale of adoption necessary to shift global fertilizer systems onto a climate-compatible trajectory.

Ultimately, the pathway to improved FUE within CSA is not one of choosing between food security and environmental sustainability. The most comprehensive analyses of this challenge consistently affirm that these goals are, with the right interventions and policies, largely complementary rather than fundamentally opposed, and that the potential to produce more food with fewer emissions and healthier soils represents one of the most consequential and achievable transformations available to contemporary agriculture.

10. Limitations

This review carries several limitations that readers should bear in mind when interpreting its findings. As a narrative rather than systematic review, it is subject to selection and interpretation choices that may not be fully replicable, even though systematic steps were taken to maximise breadth and representativeness of coverage. The geographic scope of the literature is uneven: temperate, high-income farming systems are substantially over-represented in the peer-reviewed literature relative to smallholder systems in sub-Saharan Africa, South Asia, and Southeast Asia, potentially skewing the interpretation of context-specific outcomes.

The review focuses primarily on nitrogen, with phosphorus and micronutrient management receiving less detailed treatment than their agronomic and environmental importance would warrant. This reflects the dominant focus of the extant literature but may understate the significance of nutrient balance and multi-nutrient efficiency in determining both yield and environmental outcomes. Furthermore, the evidence base on the long-term soil health consequences of the full portfolio of CSA practices under climate change remains incomplete; most available data come from relatively short-term field trials that may not capture trajectory dynamics relevant to decade-scale policy horizons.

Finally, the policy and institutional dimensions of FUE improvement are treated at a relatively high level of generality. Country-level and regional analyses of fertilizer policy reform, subsidy economics, and smallholder adoption pathways constitute an important body of literature that could not be fully explored within this review's scope. The strict verification protocol applied to all references, while necessary for accuracy, also limited the total number of sources that could be included. These limitations collectively highlight the enduring need for interdisciplinary research that integrates agronomic, ecological, socioeconomic, and political perspectives in the study of fertilizer use efficiency.

Disclaimer (Artificial Intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

Competing Interests

Authors have declared that no competing interests exist.

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